

THE PROGENITORS OF SUBLUMINOUS TYPE IA SUPERNOVAE

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ABSTRACT

We find that spectroscopically peculiar subluminal SNe Ia come from an old population. Of the sixteen subluminal SNe Ia known, ten are found in E/S0 galaxies, and the remainder are found in early-type spirals. The probability that this is a chance occurrence is only 0.2%. The finding that subluminal SNe Ia are associated with an older stellar population indicates that for a sufficiently large lookback time (already accessible in current high redshift searches) they will not be found. Due to a scarcity in old populations, hydrogen and helium main sequence stars and He red giant stars that undergo Roche lobe overflow are unlikely to be the progenitors of subluminal SNe Ia. Earlier findings that overluminous SNe Ia ($\Delta m_{15}(B) \lesssim 0.95$) come from a young progenitor population are confirmed. The fact that subluminal SNe Ia and overluminous SNe Ia come from different progenitor populations and also have different properties is a prediction of the CO white dwarf merger progenitor scenario.

Subject headings: supernovae: general

1. INTRODUCTION

Type Ia supernovae (SNe Ia) have been used to measure the age, mass density, and dark energy content of the universe (Riess et al. 1998, Perlmutter et al. 1999). This is possible because they make excellent calibrated candles — the shape of their light curves is correlated with their luminosity. SNe Ia that slowly decline in brightness (and have a lower value of the $\Delta m_{15}(B)$ parameter) are more luminous than SNe Ia that are fast decliners (Phillips 1993).

There is near-universal agreement that Type Ia supernovae (SNe Ia) are the result of the explosion of accreting CO white dwarfs in binary systems (Hoyle & Fowler, 1960), though the nature of the accretion process and the type of the secondary star remain unknown. If the age of Type Ia SNe can be identified, then it would limit the mass of the progenitor star and possible progenitor scenarios.

SNe Ia show variations in properties with environment, as noted by e.g. Filippenko (1989), Branch & van den Bergh (1993) Fisher et al. (1995), Hamuy et al. (1996), and Riess et al. (1999).

Many previous authors have attempted to estimate the age of SNe Ia, including: Oemler & Tinsley (1979; 10^7 – 10^8 yr), Bartunov et al. (1994; $\geq 10^7$), McMillan & Ciardullo (1996; $\geq 5 \times 10^8$ yr), and Yoshii, Tsujimoto, & Nomoto (1996; $0.5 - 3 \times 10^9$ yr).

The above studies assumed a single progenitor population for SNe Ia. The only way that the presence of SNe Ia in E galaxies can be reconciled with intermediate-age progenitors is if they stopped star formation relatively recently. Alternatively, as suggested by Dallaporta (1973) and Della Valle & Livio (1994) there may be two channels to SNe Ia — from both old and young stellar populations.

Hamuy et al. (1995, 1996) noticed that the slowest declining SNe only occur in spiral galaxies. However, they stopped short of claiming that the fast declining SNe are associated with an older population, since these SNe were seen in both E/S0 galaxies and spirals. Hamuy et al. 2000

also examined the relationship of SN Ia luminosity to environment, but came to no strong conclusions about subluminal SNe. In this study we focus on the most subluminal, spectroscopically peculiar SNe Ia where any age effects should be strongest, then examine other classes of SNe Ia.

2. METHOD

We compiled a list of all peculiar SNe Ia known at the time of writing. These SNe are listed in Table 1 along with their host galaxies and types. The data were primarily taken from Li et al. (2001), Branch, Fisher, & Nugent (1993), Phillips et al. (1999), the IAU circulars, and the Asiago SN Catalog (Barbon et al. 1999). We define SNe Ia as subluminal if they show spectroscopic signatures of subluminal SNe Ia such as deep, broad, Ti II around 4200 Å combined with enhanced Si II 5800 Å absorption. SN 1991bg and SN 1986G showed both of these signatures, as well as a fast-declining light curve. In the absence of published spectroscopic information, one SN in this study, SN 1996bk, was judged to be subluminal due to the fact that it has a light curve decline rate parameter, $\Delta m_{15}(B) = 1.75$, greater than that of SN 1986G (1.73). Unless otherwise stated, all $\Delta m_{15}(B)$ information in this paper is from Phillips et al. (1999).

Overluminous SNe are defined as SNe that are spectroscopically similar to SN 1999aa or SN 1991T (see e.g. Li et al. 2001), or those with a slowly declining light curve ($\Delta m_{15}(B) \leq 0.95$). These SNe show Fe III, and Si II is weak or absent. SN 1999aa shows Ca II, whereas SN 1991T does not. We note that photometry has not yet been published for SN 1999aa and that it may not turn out to be overluminous. We still retain this label for these SNe which are spectroscopically similar to SN 1991T. For this study, most SNe were classified based on spectroscopic peculiarity, not photometric light curves.

3. RESULTS

3.1. Subluminous SNe Ia

From the collection of subluminous SNe Ia, it is apparent that they favor E and S0 galaxies. Ten of the sixteen subluminous SNe Ia come from either E or S0 (E/S0) host galaxies. To calculate the probability that this is a coincidence, first we must know the chance that a random SN's host galaxy will be an E or S0 galaxy. Barbon et al. (1999) gives host galaxy statistics from the Asiago SN catalog. Out of 235 SNe Ia (including peculiars), with known galaxy types 62 (26%) were from E/S0 galaxies.

We can estimate the probability that at least 10 of 16 randomly drawn SNe Ia would be from E/S0 galaxies using the binomial distribution (Bernoulli 1713). If π is the probability that the host galaxy for a given SN Ia is an E or S0 galaxy, and we select N random SNe Ia, then the probability that at least r host galaxies will be of type E or S0 is

$$\sum_{i=r}^N P(r_i) = \frac{N!}{r_i!(N-r_i)!} \pi^{r_i} (1-\pi)^{N-r_i}$$

For $\pi = 0.26$, $N = 16$, and $r = 10$, $P = 0.2\%$. Thus the probability that it is a coincidence that 10 of the 16 subluminous SNe Ia are from E or S0 galaxies is 0.2%.

Two SNe Ia cannot be identified with certainty as subluminous due to a lack of data, but are suspicious: SN 1980I, and SN 1971I (Branch et al. 1993). If we include these uncertain events as subluminous SNe Ia, then 11 of 18 are in E/S0 galaxies and P is still 0.2%.

These data indicate that the association of subluminous SNe Ia with early-type galaxies is real. Furthermore, it is evidence that subluminous SNe Ia come from an older stellar population. This is a subtle point that deserves explanation. In the larger sample of SNe Ia as a whole, E and S0 galaxies make up only a small fraction (26%) of the hosts. As long as these hosts are a minority, one may speculate that SNe Ia come from an intermediate-age population, and SNe Ia only happen in E or S0 galaxies with recent star formation activity. However for a subsample of SNe Ia that greatly favors E or S0 hosts, these SNe Ia cannot be considered an oddity, but must be associated with some intrinsic feature of the host galaxy type. In other words, the property of E and S0 galaxies that makes them unique, an older average stellar population, must be the culprit (metallicity is likely a second-order effect, see, e.g. Höflich et al. 1998, 2000; Umeda et al. 1999; Ivanov et al. 2000).

Using line strength indicators, Trager et al. determine the age of NGC 4374, the host galaxy of the strongly subluminous SN 1991bg, to be approximately 14 ± 2.5 Gyr. This age relies on the assumption of a single burst of star formation, and is model dependent, but it seems a safe bet that star formation stopped in NGC 4374 at least 10 Gyr ago, giving us a rough lower limit for the age of the progenitor of SN 1991bg.

3.2. Overluminous SNe Ia

Several previous authors have noted that overluminous SNe Ia, such as SN 1991T, tend to favor star forming environments and may be associated with a younger stellar population (e.g. Hamuy et al. 1996). These suspicions are upheld in the data presented here.

From the Asiago catalog, 42% of SNe Ia are from Sbc or later host galaxies. In the sample presented here, if we consider all events (even those with uncertainties), then 17 of 23 overluminous SNe Ia are from this late set of hosts. The binomial distribution gives a 0.2% probability that this is a chance occurrence. If we throw out the SNe Ia with uncertainties in their classification or host galaxy type classification, and also remove SNe Ia in peculiar galaxies, then we are left with 14 overluminous SNe Ia. Of these, 12 are in Sbc or later galaxies. There is only a 0.1% probability that this happened by chance.

While no overluminous SNe Ia have been discovered in E galaxies, a few have been discovered in S0 galaxies: SNe 1998es, 1998ci, and 2000cx. Of these galaxies, the host of SN 1998ci is listed as peculiar, and inspection of CCD images reveals that this galaxy may have a distorted disk. Additionally, the host galaxy of SN 1998es, NGC 632, has evidence for a nuclear starburst and its type is uncertain (Pogge & Eskridge 1993). SN 2000cx has a more normal S0 host, but it is not a typical SN 1991T-like event since it shows a peculiar spectral evolution (Weidong Li, private communication).

There is an additional piece of evidence that SN 1991T-like objects are found in a young stellar population — the presence of circumstellar material. Five supernovae have been spectroscopically confirmed as true SN 1991T-like events (not SN 1999aa-like): SN 1991T, SN 1995ac, SN 1995bd, SN 1998ci, and SN 1999J. Of these, *all* five show signs of reddening.

3.3. Selection Effects

The SNe studied in this paper were culled from a diverse array of sources, so selection effects may not be negligible. To estimate the role of selection effects we also test SNe from a more uniform sample. Li et al. (2001b) present a sample of local SNe Ia discovered by the Beijing Astronomical Observatory Supernova Search (BAOSS) and the Lick Observatory Supernova Search (LOSS). These CCD searches were done using similar techniques and attempt to avoid many of the pitfalls of magnitude limited searches. This sample of SNe should be much less affected by selection effects than a random collection.

It is apparent that subluminous SNe Ia are preferentially located in E or S0 galaxies in this sample as well. Five of seven subluminous SNe Ia are in E/S0 galaxies, giving $P = 0.5\%$. Selection effects do not seem to be the culprit in the tendency for subluminous SNe Ia to favor older stellar populations.

3.4. Diversity in the Older Population

Figure 1 shows SNe Ia with well-determined, reddening-corrected decline rates. Host galaxy types were taken from the Asiago SN Catalog.

From this figure, it appears that the sample can be divided up into three regions, SNe Ia with $\Delta m_{15}(B) \leq 0.95$ (overluminous), those with $0.95 < \Delta m_{15}(B) < 1.4$ (normal) and those with $\Delta m_{15}(B) \geq 1.4$ (loosely-subluminous). We note that the division at $\Delta m_{15}(B) = 1.4$ may not be exact. The line could be drawn at $\Delta m_{15}(B) = 1.3$, for example. We designate SNe Ia with $\Delta m_{15}(B) \geq 1.4$ as loosely-subluminous to differentiate them from spectroscopically peculiar, very sub-

luminous SNe Ia like SN 1991bg and what may be its weaker cousin SN 1986G. We will now call these latter SNe Ia strictly-subluminous. We take the dividing line of strictly-subluminous SNe Ia at the value for SN 1986G, $\Delta m_{15}(B) \geq 1.73$.

A striking feature about Figure 1 is that strictly-subluminous SNe Ia are not the only ones that show a preference for E/S0 galaxies. For SNe with $\Delta m_{15}(B) \geq 1.4$ (and spectroscopically confirmed subluminous SNe Ia) 18 of 26 in this sample were in E/S0 host galaxies. The probability that this is a chance occurrence is 5×10^{-6} . This is interesting because SNe Ia with $\Delta m_{15}(B) \sim 1.4$ are essentially spectroscopically normal. This indicates that a dramatically different mechanism may not be at work in the normal and loosely-subluminous SNe Ia.

Overluminous SNe Ia appear to come exclusively from a younger population, while subluminous SNe Ia come from an old population. This raises an obvious question: Is the age of the progenitor star the parameter that controls the strength of the explosion? Despite the fact that old progenitors appear to be required to produce subluminous SNe Ia, they also produce fairly normal SNe Ia. Figure 1 shows that SNe Ia in E galaxies have $\Delta m_{15}(B)$ values stretching from 1.13 to 1.93. Additionally, the 10 Gyr old population of NGC 4374 that was host to SN 1991bg was also the home of SN 1957B. This SN was subluminous by about 0.9 mag in B relative to a typical SN Ia (Della Valle et al. 1998), but brighter than SN 1991bg. It had a decline rate of 1.3 mag.

4. CONCLUSIONS

Earlier findings that overluminous SNe Ia come from a young progenitor population were confirmed, as 17 of 23 are from Sbc or later host galaxy types. If we disregard SNe with peculiar and uncertain host galaxy types and SNe whose classifications are in doubt, then a remarkable 12 or 14 overluminous SNe are from Sbc or later galaxies.

We also find that spectroscopically subluminous SNe Ia come from an old population, in the case of SN 1991bg, at least 10 Gyr old. The simplest hypothesis is that all subluminous SNe Ia are from ~ 10 Gyr old progenitors, but we cannot rule out a spread of ages between $\sim 5 - 12$ Gyr. More mildly subluminous SNe Ia ($\Delta m_{15}(B) \gtrsim 1.4$) also show a preference for early-type galaxies. This is consistent with the findings of Ivanov et al. 2000.

If the progenitors of subluminous SNe Ia are ~ 10 Gyr old, then they should not exist at high redshift. For $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, at $z = 0.5$, where the bulk of SNe Ia in current studies are clustered, the age of the universe is 9.1 Gyr. Indeed, no subluminous SNe Ia are seen at $z > 0.4$ in the studies of Riess et al. (1998) or Perlmutter et al. (1999). Due to selection effects, however, we cannot conclude that the lack of subluminous SNe Ia at high redshift is due to evolution.

The finding that at least some subluminous SNe Ia must come from very old progenitors places tight constraints on their progenitor systems. Only low mass ($\lesssim 1 M_\odot$) nondegenerate stars will exist in a 10 Gyr old stellar population. It is unlikely that the following scenarios could produce SNe Ia in such an old population: hydrogen (H) main sequence (MS) stars that undergo Roche lobe overflow (RLOF) or

helium (He) MS or red giant (RG) stars that undergo RLOF (see Branch et al. 1995 and references therein, hereafter B95).

The remaining possible scenarios for subluminous SNe are hydrogen RG stars with RLOF, H stars that lose mass through a stellar wind (symbiotic stars), sub-Chandrasekhar mass explosions, and WD mergers. Sub-Chandrasekhar mass models are ruled out because they do not match observations (Höflich et al. 1996; Nugent et al. 1997). Of the remaining scenarios, each has problems. H RG RLOF systems are not thought to exist in great numbers (B95). Symbiotic stars may not exist in significant numbers in such old populations (B95), may not be accrete enough hydrogen, and should produce interaction with the circumstellar medium with has not been observed (Eck et al. 1995). Neither of the latter two cases should produce a significant number of SNe in young populations, meaning that if slow accretion to near the Chandrasekhar mass is the mechanism behind a SN Ia, then separate channels are required to produce subluminous and overluminous SNe Ia.

The finding that multiple channels are required to explain the age difference between SNe Ia is contrary to the suggestion of Branch (2001) that multiple channels are unnecessary. If there is indeed only a single channel to SNe Ia, then it must be the double-degenerate (merging WD) scenario (Webbink 1984, Iben & Tutukov 1984). In this scenario two CO white dwarfs merge to produce a Chandrasekhar mass (or greater) SN. One of the most appealing aspects of this theory is that more luminous explosions are naturally expected in younger systems (Tutukov & Yungelson 1994, 1996). This is because in younger systems more massive stars are evolving to more massive WDs than in older systems. For $t \lesssim 10^{8.5} \text{ yr}$, the average total mass of the system is expected to be $2.1 M_\odot$. SNe Ia arising from older systems would be less massive. Mergers would also be attractive for producing the asymmetries seen in SN 1999by (Howell et al. 2001), but some doubts exist as to whether or not they produce SNe Ia (e.g. Saio & Nomoto 1985).

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TABLE 1
PECULIAR SNe Ia

SN	T ^a	Galaxy	G type	Ref
1957A	u	NGC 2841	Sb	1
1960H	u	NGC 4096	Sc	1
1971I	u:	NGC 5055	Sbc	1
1980I	u:	NGC 4387: ^b	E	2
1986G	u	NGC 5128	S0	3
1991F	u	NGC 3458	S0	4
1991bg	u	NGC 4374	E	3
1992K	u	E269-G57	Sab	3
1993R	u	NGC 7742	Sb	5
1996bk	u ^c	NGC 5308	S0	6
1997cn	u	NGC 5490	E	7
1998bp	u	NGC 6495	E	8
1998de	u	NGC 252	S0	7
1999bh	u	NGC 3435	Sb	8
1999by	u	NGC 2841	Sb	7
1999da	u	NGC 6411	E	8
1999dg	u	UGC 9758	S0	8
2000ej	u	IC 1371	S0- pec	9
1937C	o ^c	IC 4182	Sm	10
1972E	o ^c	NGC 5253	Sd	10
1988G	o:	Anon.	Sc	1
1991T	o	NGC 4527	Sbc	3
1991ag	o ^c	IC 4919	Sd	10
1992P	o ^c	IC 3690	Sbc	10
1992bc	o ^c	E300-G09	Sc	10
1994ae	o ^c	NGC 3370	Sc	10
1996bv	o ^c	UGC 3432	Scd:	10
1995ac	o	Anon.	S	3
1995al	o ^c	NGC 3021	Sbc	10
1995bd	o	UGC 3151	Sc	11
1997br	o	E576-G40	Sd:pec	7
1997cw	o	NGC 105	Sab:	7
1998ab	o	NGC 4704	Sbcpec	7
1998es	o	NGC 632	S0:	7
1998ci	o	Anon.	S0+ pec:	12
1999J	o	Anon.	?	13
1999aa	o	NGC 2595	Sc	7
1999ac	o	NGC 6063	Scd:	7
1999cw	o	MCG01-02-0	Sab	8
1999dq	o	NGC 976	Sc	7
1999gp	o	UGC 1993	Sb	8
2000cx	o: ^d	NGC 524	S0	14
2001ah	o	UGC 6211	Sbc	15

^aWhether the SN is like SN 1991bg or SN 1986G and is thus underluminous (u) or like SN 1999aa or SN 1991T and is thus overluminous (o). A colon denotes uncertainty.

^bSN 1980I was between NGCs 4387, 4374, and 4406. All are elliptical galaxies.

^cPhotometric information was primarily used to make the classification. In all other cases spectroscopic information was used.

^dSN 2000cx is included for completeness, though it is not a typical 91T-like event (Weidong Li, private communication).

References. — (1) Branch, Fisher & Nugent 1993 (2) Smith 1981 (3) Asiago (4) Gomez & Lopez 1995 (5) IAUC 5842 (6) Riess et al. 1999 (7) Both Li and Asiago (8) Li et al. 2000 (9) IAUC 7532 (10) Phillips et al. 1999 (11) IAUC 6278 (12) IAUC 6921 and Nugent, private communication (13) IAUC 7096 (14) IAUC 7463 (15) IAUC 7604

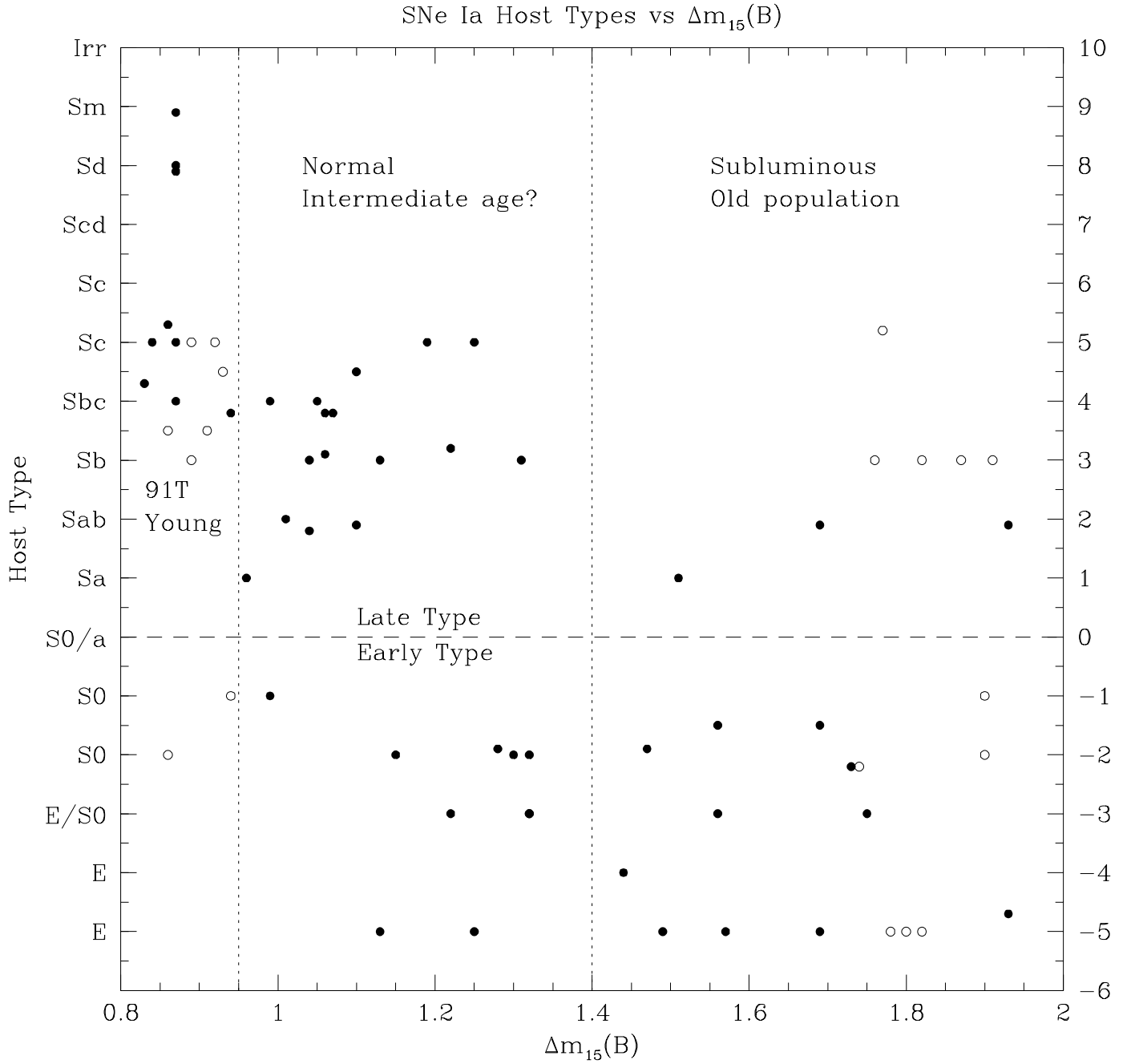


FIG. 1.— SNe Ia host galaxy types vs $\Delta m_{15}(B)$. Closed circles are photometrically determined. Open circles are spectroscopically peculiar SNe Ia for which photometric decline rates are not available. They are randomly assigned decline rates within the ranges of SNe Ia that are spectroscopically similar ($\Delta m_{15}(B) \geq 1.73$ for strictly-overluminous SNe and $\Delta m_{15}(B) \leq 0.95$ for overluminous SNe). Note that this assumes that decline rate and spectral type are well correlated (Nugent et al. 1995). Only SNe Ia with well-determined host galaxy types are plotted. SNe are plotted against T type (right axis), and the left axis just exists as a guide, so some galaxy types are listed twice.